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IMAGE RECONSTRUCTION USING LARGE ASTRONOMICAL TELESCOPES

Peter A. Strittmatter
Neville J. Woolf

University of Arizona
Steward Observatory
Tucson, Arizona 85721

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A camera, suitable for recording speckle interferograms through large optical telescopes, has been constructed. Its design and performance characteristics are reported together with the results of initial studies of the isoplanatic patch at the Steward Observatory 2.3^m telescope on Kitt Peak. The speckle pattern correlation approaches zero for objects separated by 6 arcsecs.

I. INTRODUCTION

The aim of this project is to study methoids of obtaining high angular resolution data from faint sources using optical interferometric (speckle) techniques on large telescopes. Applications are to studies of artificial satellites and astronomical objects. Ultimately, it is hoped to establish whether useful data can be obtained using large multiple mirror telescopes. During this first, single year, contract period we undertook the design and construction of a suitable speckle camera along with an image intensifier and photographic recording system. We also undertook to study the angular extent of the region over which iso-planacy is maintained through the atmosphere and to develop data handling methods for reducing the specklegrams. This work has been successfully completed and is described below.

2. THE SPECKLE CAMERA SYSTEM

A schematic of the speckle camera system is shown in Figure 1. (Detailed drawings may be obtained on request.) The speckle system consists of several independent modules; namely,

(i) the prism system to correct atmospheric refraction

(ii) the main module containing the microscope, guide alignment system, and filter trays

(iii) the image intensifier package

(iv) the recording system, currently a photographic camera.

Each of these systems will be described individually.

2.1 The Prism System

This module fits directly to the telescope mounting flange and consists of a rotating wheel in which are located four apertures, any one of which may be placed in the telescope beam by activation of a small electric motor. One

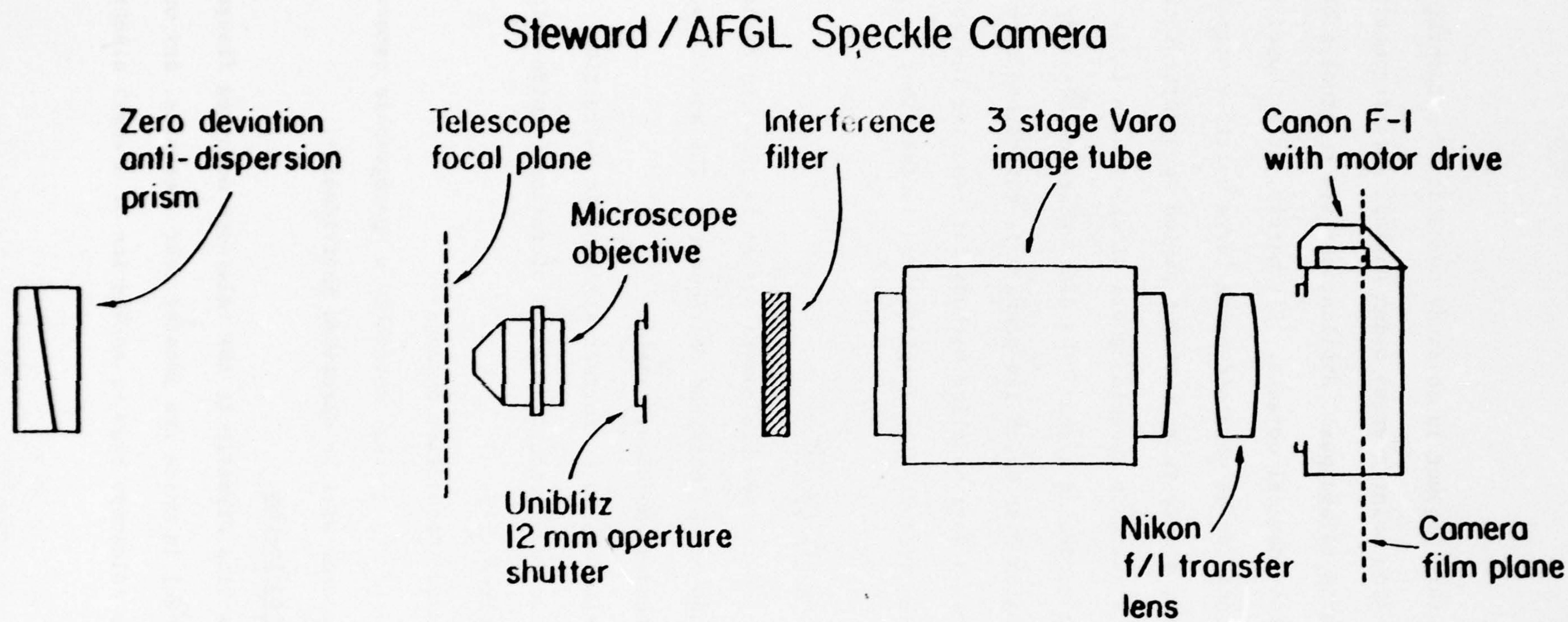

FIGURE 1

Schematic of the Steward/AFGL Speckle Camera in the photographic recording configuration

aperture is clear, the remaining three contain quartz-fluorite zero mean deviation prism mounted on rotating stages. The prism characteristics are listed in Table 1. The stages rotate on precision bearings which permit very free motion; they are also loaded with off-center weights so that except at the zenith, the prisms are automatically oriented in the direction of gravity and hence of refraction. Each prism is designed to correct atmospheric refraction to the desired accuracy (i.e., better than the diffraction limit of the telescope) within prescribed intervals of zenith distance (cf. Table 1). Thus for work near the zenith the clear aperture is selected while for zenith angles near 55° prism 3 would be used. Our experience at the 90" telescope working at f/9 has clearly demonstrated the simplicity and effectiveness of this approach. For telescopes of different effective focal lengths (e.g., the 90" at f/45, the KPNO 158"), it is necessary to introduce a spacer between the prism module and the microscope system if the prisms are to correct for the same zenith distance intervals. With this simple addition the system can be used on any telescope.

2.2 The Main Module

This module bolts directly onto theprism flange and contains a mechanical stage on which are mounted the microscope objective, a reticule and a mirror. A schematic is shown in Figure 2. In one location of the stage, the microscope objective is on the optical/mechanical axis of the entire telescope/speckle camera system. In the other, the reticule is centered on this axis and the 45° viewing prism sends the light from the telescope to a viewing eyepiece. An object may thus be centered, after which a simple motion of the stages places the system in the "observe" mode. The microscope objectives are interchangeable and a range of magnifications between X5 and X60 is available in order to accommodate different focal ratios on the same telescope.

TABLE 1

PRISM CHARACTERISTICS

Prism	θ_{SiO_2}	θ_{CaF_2}	Dispersion Compensation
1	7.18°	7.61°	0.113"
2	14°.36	15°.34	0.194"
3	21°.52	22°.87	0.344°

λ=6000Å $\Delta\lambda$=600Å

Zenith Distance	Atmospheric Dispersion	Correction Characteristics Prism	Error
0°	0.00"	0	----
10°	0.031"	0	0.031
20°	0.064"	1	0.049
30°	0.102"	1	0.011
40°	0.148"	2	0.046
50°	0.210"	2	0.016
60°	0.306"	3	0.038

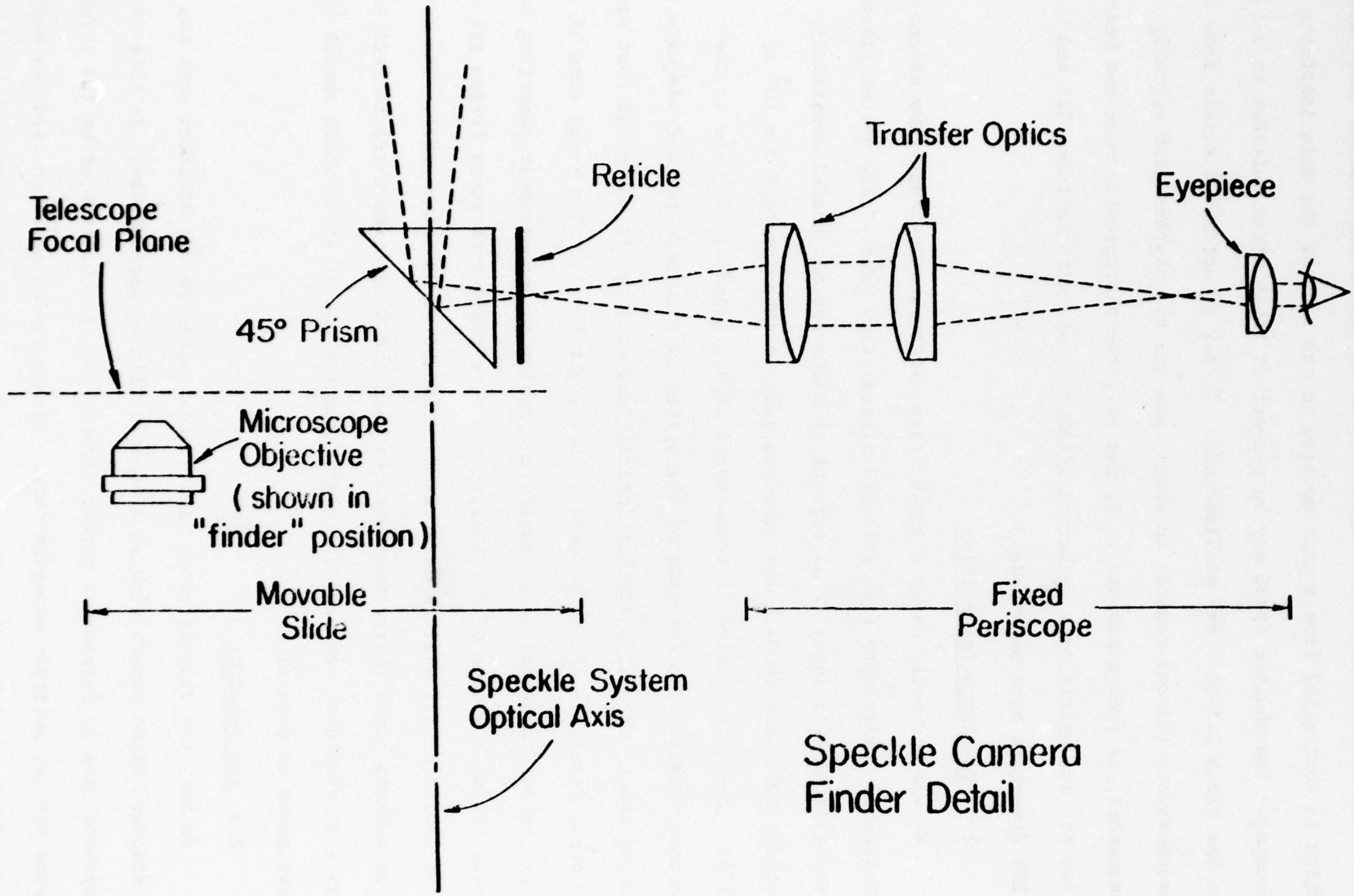

FIGURE 2

Schematic of Viewing System on
Steward/AFGL Speckle Camera

Immediately beneath the microscope is an electronic shutter (Uniblitz) which is controlled from a unit mounted to the side of the main instrument housing. The shutter speed may be pre-set on thumb wheel switches to values in the range $2.5 < \Delta t < 999$ milliseconds. It may be activated either from the photographic (Canon) camera, in which case the two shutters are suitably sequenced, or from a computer. So far only the photographic mode has been used for scientific data gathering although tests with Reticon (ID) and CID (2D) detectors have been made.

2.3 The Image Intensifier

We are currently using a three stage electrostatic image tube assembled at Steward Observatory from selected single stage Varos. The system gives a peak quantum efficiency of 11 percent at 5500A and has useful sensitivity between 2000A and 8000A. The luminous gain is approximately 5×10^5 at 5500A. The output image is transferred with a Repro-Nikkor lens to the detector plane. The net gain of the system in this mode is just adequate for photographic work but a further intensification stage is needed if fast scanned Si array detectors are to be used at low light levels. The decay time of the three output phosphors again causes no problem in photographic recording but could become a source of difficulty when very rapid contiguous frames are taken (e.g., with an SIT vidicon detector at standard 60 Hz frame rate). The intensifier systems needs improvement both in gain and decay time characteristics. It has also precluded work at wavelengths shorter and of 4000A which should be investigated at some time.

2.4 The Detector

So far, the only detector used at the telescope for standard work has been a standard Canon camera with an automatic film advance system. In this mode the exposure rate is determined either directly by the observer or by the three frame per sec multiple exposure rate. The recording emulsion used has been Kodak Tri-X in either 36 or 256 exposure cassettes. The emulsion was developed

in D19 although early experiments indicated that MWP2 was superior in insuring the highest detective quantum efficiency at low light levels. With this system good quality specklegrams can be obtained of stars down to 6th-7th magnitude. Beyond this point, however, the density of recorded events declines rapidly, partly as a result of reciprocity failure in the film and the number of frames required to insure sufficient signal to noise becomes inconveniently large. Detector improvements are clearly required for the lower light levels. Initial tests with a digital CID camera (see Section 5.1) appear promising and data have been obtained on the faint satellites of Saturn.

3. STUDIES OF THE ATMOSPHERIC MODULATION FUNCTION

One of the major questions concerning image reconstruction with large astronomical telescopes is the size of the iso-planatic patch - the angular extent of the region over which the atmospheric modulation of the incoming light wave is the same. This is crucial in certain image reconstruction techniques involving a nearby point source to determine the atmospheric transfer function (Liu and Lohmann 1973, Weigelt 1975). It is also fundamental to understanding the behavior of the atmosphere and hence the general limitations on speckle techniques.

Our technique has been to observe a series of bright binaries with separations in the range 2" - 10" arcsecs. Only systems in which both stars were brighter than 6th magnitude were used and preference was given to pairs of approximately equal brightness. The objects are listed in Table 2. The data were recorded on photographic emulsion and later digitized using the PDS scanner at Kitt Peak National Observatory.

TABLE 2

WIDE DOUBLES

Star		Magnitude V_1	V_2	Separation (arcsecs)
γ	Vir	3.65	3.68	4.05
γ	Leo	2.61	3.80	4.30
ξ	Cnc	5.56	6.02	5.97
ζ	UMa	4.41	4.87	3.03
α	Gem	1.99	2.85	2.10
11	Mon	4.60	5.22	7.4
			5.60	2.5

Our method of analysis was as follows: For each frame, the autocorrelation of each star in a binary system was calculated along with the cross-correlation between the two stars. The results were denoted by A(1), A(2), and C(1,2). Each of these functions contains a high spatial frequency component arising from the "diffraction" limited speckle pattern together with a low frequency component representing the scale and distribution of the seeing disk S(1), S(2), S(1,2). This latter component may be evaluated from the cross-correlation of any stellar image on successive exposures, or ones more widely separated in time. A measure of the speckle autocorrelations and cross correlation a(1), a(2), and c(1,2) respectively, are:

$$a(1) = A(1) - S(1)$$

$$a(2) = A(2) - S(2)$$

$$c(1,2) = (C,1,2) - S(1,2)$$

These quantities were then averaged over all frames of a given object. The averaged functions $<a(1)>$, $<a(2)>$ and $<c(1,2)>$ are plotted in Figures 3 and 4 for the binary stars γ Vir and Zeta Cnc with separations 4.05" and 5.97" respectively. Note that in ζ Cnc there is essentially no remaining correlation at a separation of 6.0". The results of all the stars in the sample may be parameterized by the function

$$\gamma(\theta)=<c(1,2)>/<a(1)\ <a(2)>)^{1/2}$$

where θ is the separation of the two stars. The results for all stars observed are shown in Figure 5. Although there is substantial scatter at a given separation, there does appear to be an upper envelope to the data which declines from approximately 0.5 at 2 arcsecs to essentially zero at 6 arcsecs. We have also made some effort to determine the dependence of γ on zenith distance. The results shown in Figure 6 indicate no obvious trend over angles less than 45° but more data are required to confirm the result.

We conclude therefore that:

(a) the size of the iso-planatic patch at the Steward 90" telescope at Kitt Peak is < 6 arcsecs in typical conditions;

(b) substantial correlation exists out to 4.5 arcsecs;

(c) the correlation at any given separation varies with time.

4. DATA ANALYSIS

Our main efforts in this area have been directed towards developing software to process 2-D analogue frames such as digitized photographic data. The program, (SPEKL), is described briefly below:

The reduction program uses the method of autocorrelating each short-exposure frame to recover information of high spatial frequency and using the

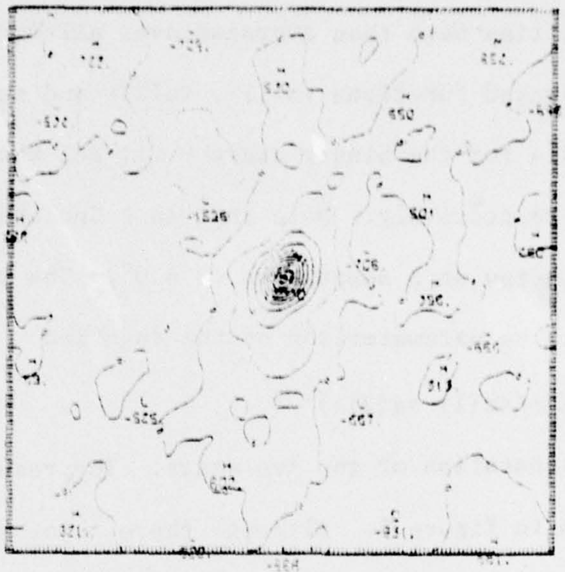

Figure 3a

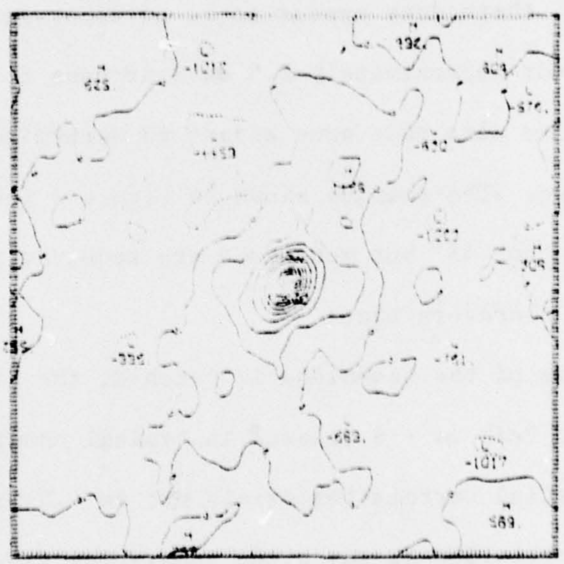

Figure 3b

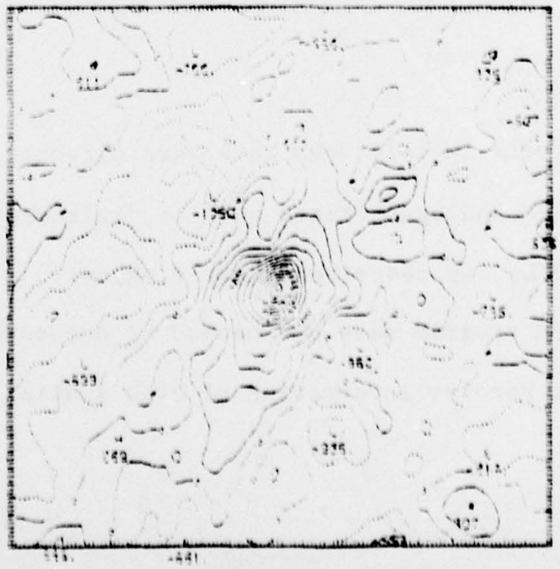

Figure 3c

FIGURE 3

The autocorrelation a(1) and a(2) and the cross-correlation c(1,2) for the binary star γ Vir A and B are shown in Figs. (a), (b), and (c) respectively. The separation of components A and B is 4.05 arcsecs.

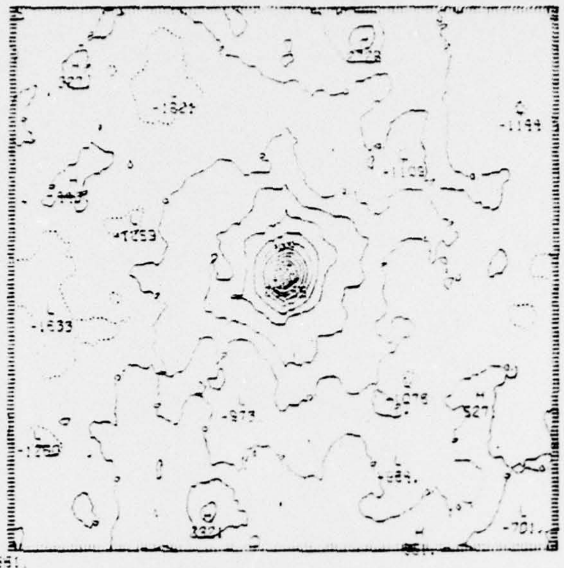

Figure 4a

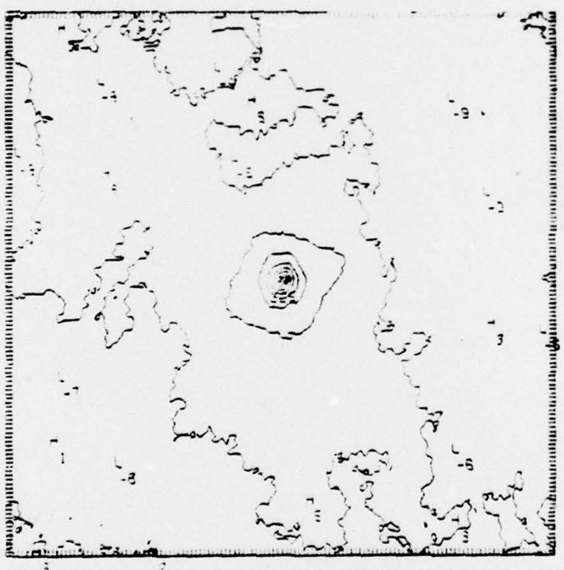

Figure 4b

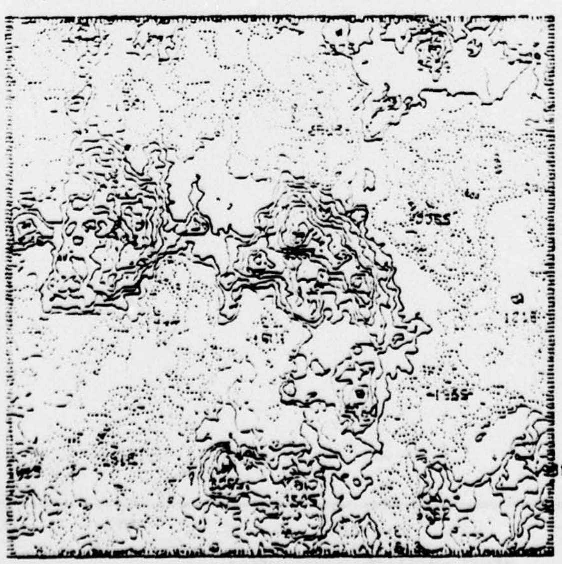

Figure 4c

FIGURE 4

The same as Fig. 3 but for the binary star ζ Cnc with a separation of 5.97 arcsecs. Note that there is essentially no remaining correlation at this separation.

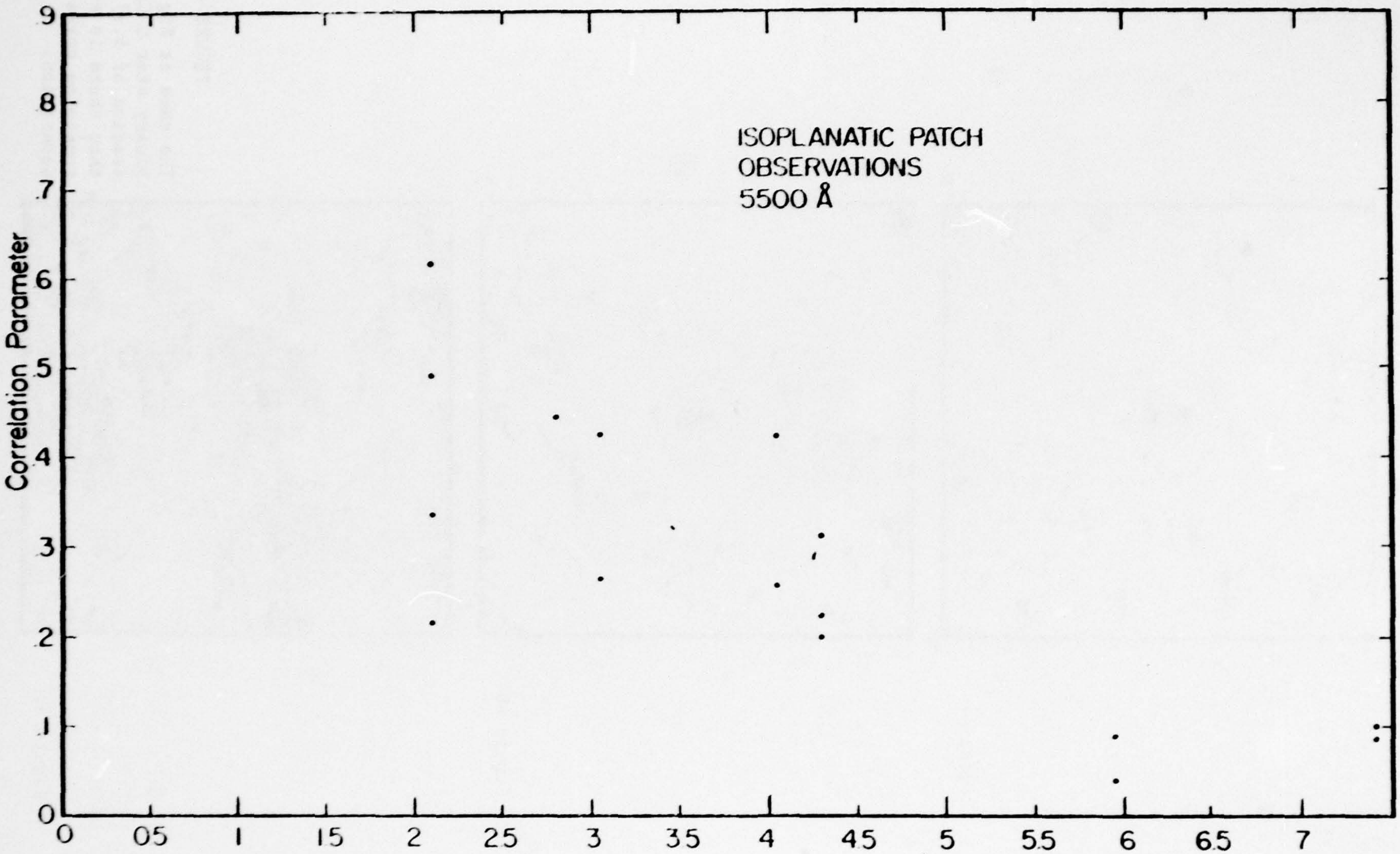

FIGURE 5

The correlation parameter γ (θ) as a function of separation in arcsecs. The results show considerable variation at a given separation but seem to suggest an upper envelope to the correlation which has approached zero at approximately 6 arcsecs.

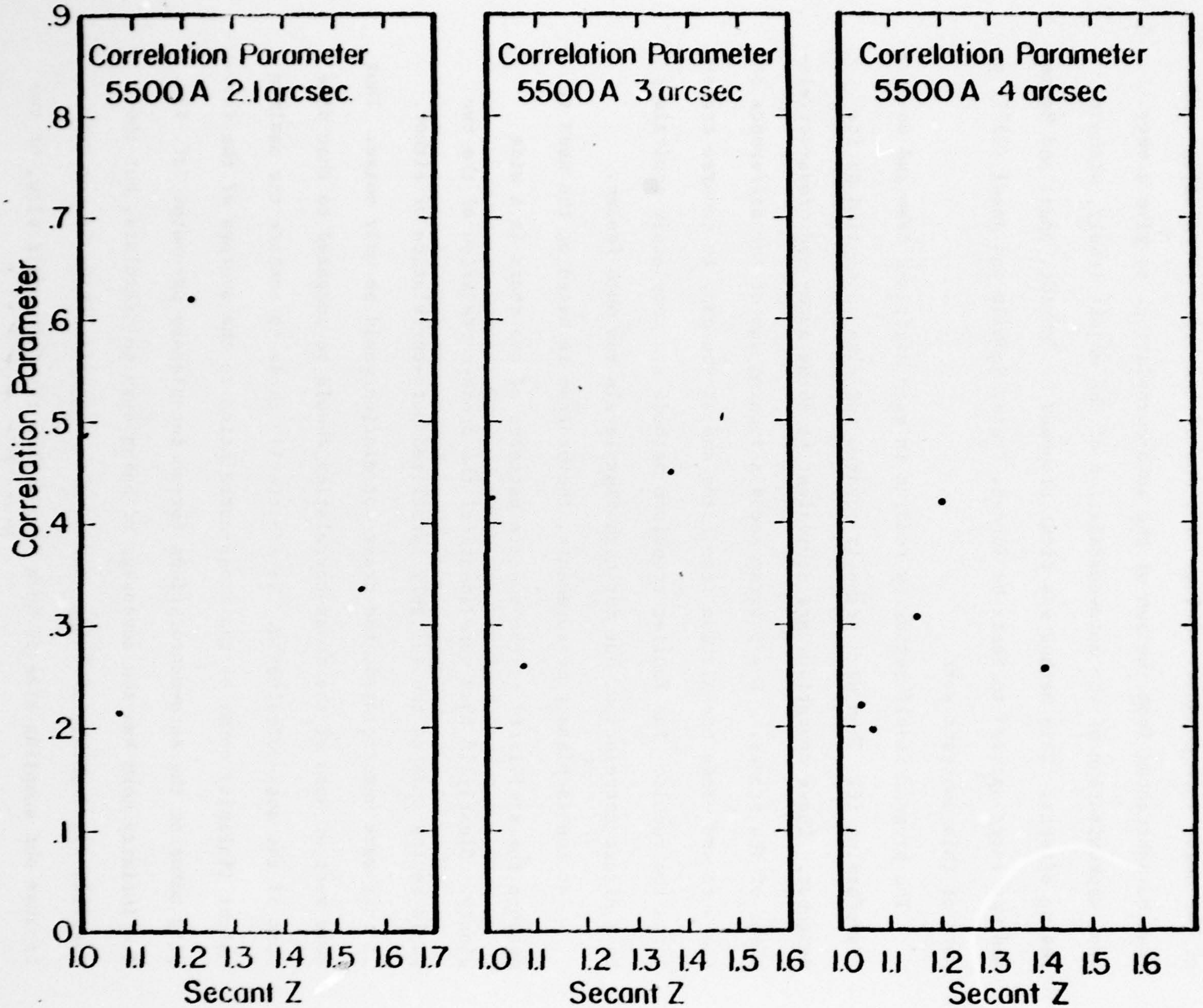

FIGURE 6
Preliminary results on correlation as a function of zenith distance indicate no obvious dependence on this quantity.

cross-correlation of each frame with the (n+1)th frame as an approximation of the noise introduced by seeing. The sum of the cross-correlations can then be subtracted from the sun of the auto-correlations to give a very good approximation of the auto-correlation of the object itself, without seeing effects. This method was first proposed by Schmidt, Angel and Harms and was later applied to Vesta by Worden, Stein, Schmidt and Angel (1977) as part of this contract work.

The program itself begins by reading in each digitized fram and Fourier transforming it. Then each frame is squared and also multiplied by its neighbor. These operations are equivalent to doing auto- and cross-correlations of the frames. The program keeps a running sum of the difference of the auto and cross correlation transforms and at the end, it inverse transforms the result. The Fourier transform methods are completely equivalent to a direct correlation, but for high flux levels run much faster.

For the isoplanacy measurements, the program is based on the need to measure the similiarty of the speckle patterns of two stars in a wide binary. Clearly if they were identical the cross-correlation of the two would be the same as the suitably normalized auto-correlation of either. If they were uncorrelated, the cross-correlation would be only noise. Thus, some sort of norm of the cross-correlation should be compared to that same norm of the auto-correlation. We arbitrarily chose to compare the maximum height (infinity norm) of the cross-correlation to the average of the infinity norms of the auto-correlations for an iso-planacy parameter (cf. §3). The infinity norm has the advantage of being easy to calculate, but the possible disadvantage of being sensitive to the noise spike in our data because our sampling size is much larger than the film grain size, or the photon size on the film.

At the high photon rates (i.e., rates in which more than one photon arrives per speckle/frame on average) a similar processing scheme is required for digital data also. In this situation the analysis time turns out to be longer than the frame time. In the event that the number of photons per frame is low, however, it becomes possible to calculate the auto-correlation directly in a time shorter than the frame time. An experiment has been carried out at the 90" using only a linear array, thereby losing much of the available information (Schmidt, Angel and Harms 1976). It nontheless was clearly demonstrated the on-line calculations of the auto-correlation function could be carried out at the telescope.

We conclude that if processing is carried out in the computer there is a natural division between low flux studies where auto correlations can be carried out on line without wasting observing time. The information per frame is in any case low, many frames are therefore required, and telescope time is crucial. For bright objects the number of frames required is lower but the processing cannot occur in real time in the computer. Telescope time is wasted if on line results are desired. The only way in which telescope time can be conserved is by using hard-wired Fourier Transform devices in which the incoming data is processed before stacking (co-adding) in the computer.

5. PROBLEMS AND FUTURE WORK

In carrying out the program described above, we have encountered a number of problems and discovered several areas for further investigation.

5.1 Detector System

Our most serious problem has been the use of a photographic recording system. The difficulties arise because of the following:

(a) the non-linear responses

(b) the low dynamic range

(c) the slow frame rate compared to frame time (inefficient data gathering)

(d) the immense data reduction task when only a few photons are recorded.

The above problems limit the efficiency and accuracy of recording data and render work on fainter objects prohibitive.

These deficiencies can be remedied by the introduction of a linear electronic recording system capable of measuring either analogue signals (high photon rates) or the locations of individual photons. Such a system might be constructed using 500 x 500 pixel solid state array (CCD or CID) readouts of high gain image tubes. In our system, it would merely replace the photographic camera. It is hoped to construct such a readout system during the next grant period. In the meantime, some preliminary detector work has been carried out.

Photoelectronic Detector Development

A 2 x 936 Reticon photo diode array and a 128 x 128 GE charge injection device (CID) image sensor have been successfully implemented as secondary sensing elements for photoelectron limited data acquisition. Both of these devices are transfer lens coupled to the output of the equivalent of 4 or more stages of Varo photoelectronic image intensifiers to provide the primary photoelectronic detection and optical signal amplification necessary to overcome the electronic readout noise intrinsic to such devices. The Reticon photodiode array has been implemented in a one-dimensional mode as a possible precursor for a Reticon 2-D array. The CID device has been demonstrated

as an image sensor for 2-D speckle interferometry camera in both analogue and photon counting modes. These systems are described briefly below.

The Reticon System. The Reticon CP1001 silicon photodiode array consists of two parallel adjacent rows of 936 diodes each. The diodes are 30μm long (contiguous along the row) and 375μm wide. The active area is thus 0.750 mm wide x 28 mm long. The arrays are scanned sequentially under computer control. Each array is readout in two analog channels through low-noise charge-sensitive FET-input preamplifiers. In order to reduce the detector dark current the entire array and preamplifier package is cooled to -35°C. To minimize readout noise, the arrays are scanned at a maximum rate of 4 KHz (250μ-sec per diode) allowing analogue filtering to 20 KHz bandwidth, yet permitting an 8 KHz data rate since odd and even diodes are read simultaneously. This permits operation with a 14 bit A/D converter at a dynamic range (ratio of maximum signal to read-out noise) of 104 to 1 with a readout noise of approximately 700 electrons per photodiode.

This system is currently used as an analog readout device to record 1-D data obtained at the 90" telescope Cassegrain focus. The spectrum or object is initially imaged onto an RCA two-stage 40 mm magnetically-focused image tube, and the phosphor output of the tube is re-imaged, using an f1.0 Repro-Nikkor 1:1 transfer lens, onto a Varo three-stage 40 mm intensifier. The phosphor output of the Varo tubes is in turn imaged by a second f/1.0 Repro-Nikkor 1:1 transfer lens onto the Reticon photo diode array. The Varo tubes are magnetically shielded from the RCA tube, and one stage of the Varo tubes is equipped with a pair of coils which translates the spectrum along the photo diode array in order to over-sample the spectrum. Deflection of the spectrum by one-half diode width, i.e., 15μm, comfortably oversamples the

$65\mu m$ resolution obtained with a 2.5 arcsecond spectrograph aperture. With both transfer lenses at f2.8, approximately 1.5×10^4 electrons are produced in the detector for each photoelectron. Since the readout-out noise is about 700 electrons, individual photoelectrons are detected readily. The diode saturation charge is approximately 2×10^7 electrons, thus the effective detector dynamic range, at these transfer lens settings, is approximately 1300:1.

In order to further minimize the detector noise, the image tubes are cooled to about -15°C to reduce photoelectronic dark emissions and ion events. A computer algorithm makes it possible to identify and remove the large amplitude signals (typically 10 to 100 times that of photo electrons) produced by ion events by comparing a given detector scan with ones immediately preceeding and following it. The variations in diode-to-diode sensitivity of the Reticon, amounting to about 5% rms, are calibrated by observing a continuum lamp. The total system response function is determined by observing photometrically calibrated standard stars.

The device is readily generalizeable to 2-D formats more suitable to speckle work. Such arrays will soon be available from the Reticon Corporation.

The CID System. The central component of the General Electric TN2200 CID camera is a 128 x 128 element array of pixels on $46\mu m$ centers giving a square sensor 5.9 mm on a side. This camera may be readout at a maximum rate of forty frames of 16,384 elements per second (0.6 MHz) externally clocked by its control unit.

The computer supervised camera control used here contains a four microsecond 8 bit A/D converter with selectable clock rate and other logical controls for a high-speed shutter and other auxiliary equipment. Between the

camera control and the actual interface to the control computer there is a high speed 8 bit multiplier which can be bypassed or inserted into the digitized video data path or may be made available directly to the processor for high speed 8 bit multiply operations.

The control computer is an 8 bit Z-80 microprocessor capable of 4 MHz operation coupled to a 64K 300 nsec static RAM memory. This memory is sufficient to hold image acquisition and analysis programs and still have room for two completely digitized frames of data. An on-line video display consisting of a simple XYZ (X, Y, Intensity) monitor capable of displaying 8 bit digitized data on all three axes is included. This image acquisition system is linked by a data-interface to a host computer for recording frames on disk and magnetic tape and for other data reductions. With the microprocessor running at its 4 MHz clock rate, the system is capable of acquiring and storing 8 bit digitized pixel data for a complete 17,384 element frame in 80 msec.

When the camera is operated at -25°C the camera noise is significantly less than the least significant bit (l.s.b.) of the 8 bit A/D converter. In the configuration used with the speckle camera application, the primary camera image was acquired with a three-stage 40 mm Varo image intensifier. The phosphor output of the image intensifier was reimaged on a second three-stage 40 mm Varo image intensifier using an f1.0 Repro-Nikkor 1:1 transfer lens. To reduce dark emissions, the image intensifiers were operated at about -15°C. With both transfer lenses at f 1.4 single photoelectron events can be imaged on single pixels with amplitude of more than 100 l.s.b.

A version of this system has just been tried out at the telescope. First indications are that good speckle data were obtained although a proper

evaluation awaits detailed reduction. The system has two apparent disadvantages; namely a fairly slow frame time (2 secs at present although this can be improved to ~ 0.5 secs at low flux rates) and only marginally adequate numbers of picture elements for use at a ~ 100" telescope. For larger telescopes a 256 x 256 array will be necessary. Nonetheless, the present system offers valuable experience and an apparently useful interim solution to the detector problem. For the longer range we are continuing our interest in SIT Vidicon, Reticon arrays and large format RCA-CCD systems.

5.2 Atmospheric Effects

In the course of our analysis we have come across a number of further tests that need to be made to fully assess the power of the speckle technique. They are:

1. How long an exposure can be made without loss of information? How does this depend on light level?
2. How many speckles on average contain above a specified fraction of incident photons?
3. Is there good radial symmetry in the extension of speckles when broad band passes are used? If so, can lenses be used to correct this as suggested by Dainty?
4. How does the size of the isoplanatic patch vary with telescope aperture?
5. Why does speckle contrast seem to decline at shorter wavelengths and how does this limit interferometric studies?

These questions will be addressed during the new grant period.

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